APPLICATION OF IONIZATION PROBES FOR DIAGNOSTICS OF KNOCKING COMBUSTION

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Abstract
The possibility of knock diagnostics with an ionisation probe technique is demonstrated. Ionization probe signals obtained in autoignition zone and in burned gas at different amplitude and polarity of bias voltage have been analysed. Obtained probe current-voltage characteristics showed that in autoignition area the current to probe is formed by the drift of positive or negative ions, depending on the polarity of bias voltage. It was suggested that during autoignition the current to probe occurs mainly due to chemi-ionisation in the flame and probe current is controlled by flame ionisation density and drift of ions via flame quenching layer to the probe surface. Based on this approach, current amplitude in zone of autoignition was predicted and compared with experiment. We found that variations of relative current value with pressure obtained numerically and experimentally correlate well. In zone of burned gas the behaviour of probe current-voltage characteristics indicated the presence of electron component of probe current. It allowed suggestion that in burned gas the main source of charged species would be thermal ionisation behind the transient shock waves. Evaluation of probe current at these conditions allowed prediction of relative variation of probe current with pressure in burned gas area. Simple analytical models were also suggested to predict the amplitude of pressure peak in zones of autoignition and in burned gas. Correlation between probe current and pressure signals in zones of autoignition and burned gas is discussed.

Introduction
As a result of the growing need to improve the performance and efficiency of spark ignition (SI) engines, the knock phenomenon is the subject of study since decades. During knocking combustion, non-controllable autoignition of fresh combustible mixture takes place before the flame front. Knocking combustion regime is extremely undesirable in SI engine because it impairs the combustion efficiency [1]. Moreover, rapid volumetric energy extraction leads to the birth of micro-explosions in the end gas and shock waves propagating through the combustion chamber [2]. Large mechanical loads due to the local increase in gas pressure and temperature can cause serious mechanical damage of engine [1].

Although a number of techniques exist for detection and control of knocking combustion to avoid this regime, it remains a major challenge in engine management system [3]. Because knocking regime is characterized by the high-frequency, high pressure oscillations inside the cylinder, in-cylinder pressure monitoring of each cylinder using piezoelectric instrument grade pressure sensor is commonly practiced for detection of knock. However, this technique is well adapted to the laboratory conditions. In-cylinder pressure measurement is not typically available option for production engines due to the high cost of the sensors and the requirement that each cylinder has its own sensor.

Pressure oscillations transmitting through the engine body cause vibrations that can be detected by means of an accelerometer installed in the engine block. In this way several cylinders can be controlled with only one sensor. However, knock induced vibrations must be distinguished from mechanically induced structure vibrations which can occur even during normal combustion. A careful selection of the most appropriate sensor location and signal processing technique is therefore required.

A heat release analysis method was also proposed for knock detection [4, 5]. The intense local heat release due to end-gas autoignition, which causes a substantial shift from the normal combustion heat release profile, has also been extensively investigated in order to find possible knock indicators. However, the computational complexity required to determine the rate of heat release is not compatible with real-time knock detection: therefore simplified techniques have also been proposed in [4], which allow the detection of anomalous heat release rates by means of easier pressure derivation methods.

It is worth noting that the majority of used knock detection methods generally based on the pressure and vibration measurements, or their variations [3]. Therefore these methods can't be widely used due to high cost of the sensor.

Alternative methods have therefore been investigated, such as techniques based on gas ionisation analysis: the spark plug can be used as an ionization probe, by measuring the corresponding current, in order to detect abnormal combustion phenomena through the sharp increase in ionization [6]. Conventional spark plug as ionization sensor mounted in the cylinder wall was used in this work. It was mentioned that, looking at the ion current waveform, it was difficult to detect knocking high frequency directly from observed waveforms. But knocking can be easily observed by signal passing through a band-pass filter of a frequency corresponding to the knocking pressure oscillations. Some difficulties related to the determination of knock intensity from the amplitude of ionization current ware mentioned. In [7] the analysis of correlation of ionization signal in reference to the cylinder pressure signal was carried out. The ion and pressure signals were characterized and compared through the use of frequency analysis, correlation, and coherence. The results of [7] showed that the correlation and coherence are low as a result of both the ion and pressure signals being point measurements. Nevertheless, correlation of knock levels between the ion and cylinder pressure was found through the statistical analysis.

From results of [6, 7] one can conclude that knock detection by ionization sensor is ambiguous and additional study is needed for characterisation of knocking from ionization probe current signal. In particular, one has to take into account the relative position of ionization and probe sensors. From our point of view, the correlation between both signals must be analyzed at the same conditions in vicinity of probes. It is important because the waveform and amplitude of pressure and ionization current signals can be different when probe is located in zone of autoignition or in burned gas. Some distinctive features of probe current formation also can be taken into account [8-10]. These problems forestall using ionization probe technique for knocking detection and are the subject of study in this work.

Experimental set-up

Experiments were carried out with steel static volume heated combustion chamber 172x40x40 mm^3 (Fig.1). A number of cylindrical heaters of total power 120W, mounted in the lateral chamber walls, allowed chamber heating up to 200°C. The temperature of chamber walls was controlled with thermocouples mounted in chamber walls. At the wall temperature 140°C the non-uniformity temperature field on the internal wall surface of combustion chamber was not exceed 4-5°C. The measurements of gas temperature distribution in the combustion vessel showed the uniformity of temperature field, standard derivation of gas temperature was about 4%.

Combustion chamber had the possibility to mount pressure gauges or electrical probes in the chamber walls. The positions of gauges allow measurements at different combustion chamber cross-sections: 40mm and 85mm from the chamber top as well at the chamber bottom. Thanks to such positions of probes simultaneous measurements of pressure and gas electrical properties were realised the in zone of autoignition and in burned gas. Kistler pressure gauges of 601H type were used for the measurement of pressure time evolution during combustion. Conventional spark plugs with one external and one central electrode were used as electrical probes. Central electrode of spark plug had 2.5mm in diameter and 1.5mm in height. The gap between electrodes was 1mm. Spark plug which was similar to one for current measurements was used to ignite combustible mixture at the chamber top, at the distance of 5mm from the upper wall. Ionization current to the probe was measured by resistance of 10kOhm inserted in electrical circuit of electrical probe. During each test, bias voltage, U_{bias}, applied to electrical probe was constant. Experiments were carried out with bias voltage in the range from -100V to +100V.

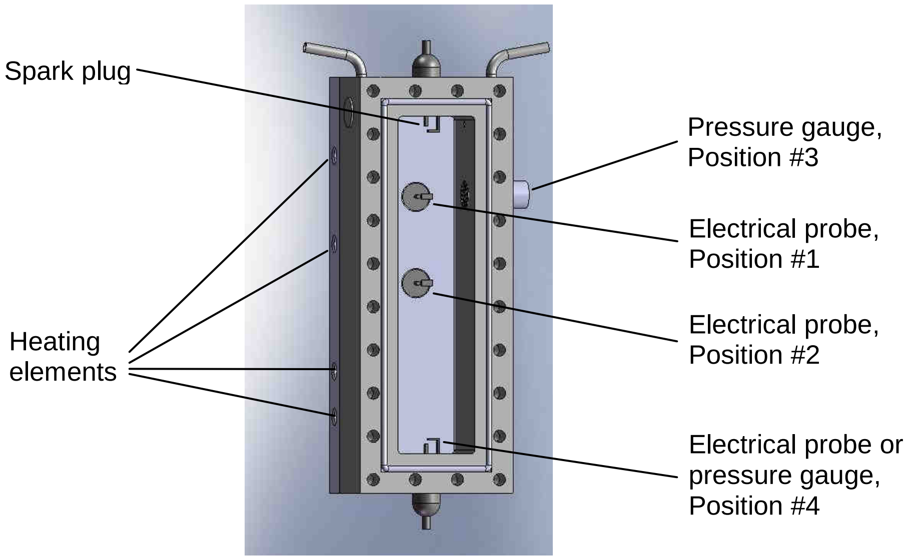

Figure 1. Sketch of combustion chamber.

During the test the quiescent heptane/oxygen stoichiometric mixture was ignited by automotive spark plug placed at chamber top. To obtain knocking regime, tested mixture was diluted by Argon in ratio 1:3.45. Mixture making procedure was carried out in storage vessel heated to 80°C to avoid heptane condensation. Before the test, C_7H_{16}/O_2/Ar mixture was injected to the combustion chamber via pipes heated to 80°C. Knock combustion regimes were studied at an initial pressure 0.4-1MPa. In all tests the temperature of chamber walls was kept at 140°C.

Results and discussion

Similar to detonation studies, the visualization of knocking combustion was realized with smoked plates mounted at the side walls of combustion chamber. The size of plates placed at the side wall was 70x40mm^2.Typical images of soot traces are shown in Fig.2. The traces on the soot plates were caused by pressure (or velocity) gradients along the plate surface. More bright parts on the plates correspond to the area of higher gradients.

It is evident that the structure of knocking area is rather complex. It creates difficulties for the detailed analysis of soot trace images. Nevertheless, in the images presented in Fig.2 we should resolve a zone of autoignition "A". This zone is dark because soot layer was not removed here. It means that in zone "A" the pressure (or gas velocity) gradient is absent or directed perpendicular to the plate surface. It means that autoignition zone is placed in vicinity of the bottom plate or this zone is located at some distance from the bottom and expands perpendicular to the bottom surface. In Fig.2 we should easily detect the propagation of shock waves and its interference in burned gas (zone "B"). The wave structure detected in zones "C" corresponds to the package of transversal waves propagating perpendicular to the longitudinal chamber axis. It is worth noting that in our tests autoignition zone was always located at the bottom of combustion chamber. The thickness of this zone varied from shot to shot but in all tests was not exceed 3cm.

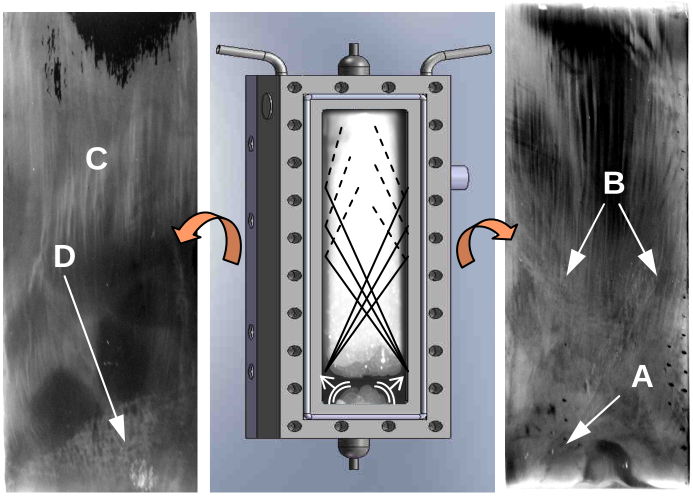

Figure 2. Soot traces of knocking: A- zone of autoignition, dashed line schematically shows the border of this zone; B – shock waves; C – traces of transversal waves; D – irregular cell structure. Initial pressure is 0.85 MPa.

Based on the results of soot trace analysis a simplified model of autoignition process would be proposed. We suggest that spontaneous volumetric autoignition of the end-gaz occurs at the centre of the chamber, in vicinity of the bottom. Autoignition produces numerous compression waves transforming in shock waves (see central image in Fig.2). Combustion fronts move with acceleration behind shocks running down them. This process is similar to, probably, deflagration-to-detonation transition. Nevertheless, the formation of stationary detonation wave propagating in fresh mixture is not evident due to a small spatial size of end-gas zone. After the entrance in burned gas area, compression waves associated with combustion reaction front continue their propagation as shock waves. These waves reflect of the side walls and interact. During propagation along combustion vessel, the intensity of shock waves decays as waves are damped out.

In our consideration we suppose that the process of spontaneous autoignition is similar to constant volume combustion. In this zone a chemi-ionization due to combustion would be the main mechanism of gas ionization. So, the model of flame/probe interaction developed in [8] would be used for the analysis of ionization current to the probe located in position #4. Because in burned gas the combustion reactions are finished, in this zone the ionization probe signal would be related to the thermal ionization of gas behind the shock waves.

Typical electrical probe signals obtained in autoignition and burned gas areas are shown in Fig.3. Two couples of oscilloscope traces are presented in this figure. One couple of signals (Fig.3a) corresponds was recorded by electrical probe located in position #2 (burned gas zone). Other couple of ionization probe signals (Fig.3b) was obtained with ionization probe placed in position #4, i.e. in zone of autoignition.

In position #2 electrical probe detects first the arrival of incident flame front (it corresponds to the first step of relatively low amplitude – see Fig.3a). This changing in amplitude of current is due to chemi-ionization occurred in the flame front. Next “plateau” in recorded trace of probe signal corresponds to the thermal ionization of burned gas. The following peak of very high amplitude is related to the passing of shock wave increasing significantly gas ionization density.

In contrast to the burned gas zone, in zone of autoignition the electrical probe detects chemi-ionization process occurred in flame (see Fig.3b). In autoignition zone probe signal is characterized by higher amplitude than that in burned gas.

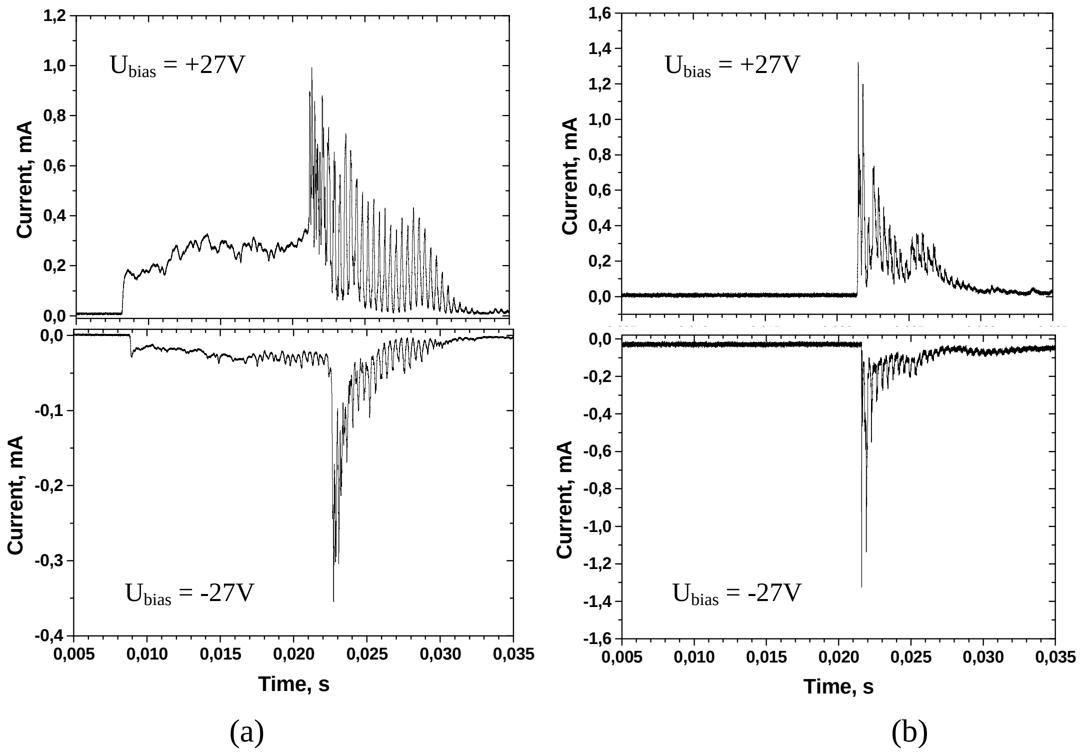

Figure 3. Typical oscilloscope traces of probe current in burned gas (a) and in zone of autoignition (b). Upper and lower traces corresponds to U_{bias} = +27V and U_{bias}=-27V, respectively. Initial pressure is 0.7 MPa.

One of intrinsic questions during ionization probe measurements is the choice of the polarity and value of probe bias voltage. In Fig.3 the oscilloscope traces of electrical probe signal in burned gas and in autoignition zone are shown for different polarity of bias voltage, U_{bias}. The shape of current signal is significantly different when positive or negative U_{bias} is applied. As it was mentioned in [8, 11] the size the sheath layer would depend on the type of charge carriers collected by probe. When probe is charged positively it collects electrons and negative ions. In this case, due to higher electron's mobility, the spatial area affected and, consequently, analyzed by probe would be larger than one for negatively charged probe (then probe current is due to the drift of positive ions only having much less mobility in contrast to electrons). At some conditions, when electron component of current is absent, the amplitude of probe signal depends on the ionic composition of plasma. This is why the profiles of probe current signal during knocking are different at positive and negative polarity of U_{bias}. Typically, negative U_{bias} is preferable to apply to probe: by this way the local measurements of plasma parameters occurs and theoretical approach for the analysis of ion current is simpler.

The influence of bias voltage polarity on the probe signal is also illustrated in Fig.4 where typical probe current is compared with the corresponding pressure signal. Probe current and pressure time evolutions shown in Fig.4 were obtained in different tests but at the same position of gauge, i.e. at the bottom of combustion chamber, in autoignition zone. In Fig.4 both signals are given in arbitrary units. The initial level of pressure corresponds to P_c value. It is evident that the frequency of current oscillations correlate well with pressure ones.

Nevertheless, the amplitude of current oscillations sometimes significantly differs from the pressure oscillations. In contrast to pressure signal, at the beginning the amplitude of current oscillations decreases more slowly in time for negatively biased probe (compare the first and the second peaks in Fig.4a). For positive U_{bias} (Fig.4b) the amplitude of pressure and current oscillations correlates rather well for exception of the first peak corresponding to chemi-ionization in autoignition zone. For negative U_{bias} this correlation is less evident. Note that in Fig.4 current and pressure oscillations following after the first peak correspond to shock wave propagation in burned gas. The frequency of these oscillations corresponds to the frequency of shock wave propagation along the chamber. Nevertheless, some peaks are "thin" structure corresponding also to transversal shock wave propagation. The correlation between relative values of pressure and current, especially for positive probe bias voltage allows conclusion that in burned gas the negative current varies in accordance to electron and negative ion density variations which are linear function of pressure (under suggestion that gas temperature varies insignificantly).

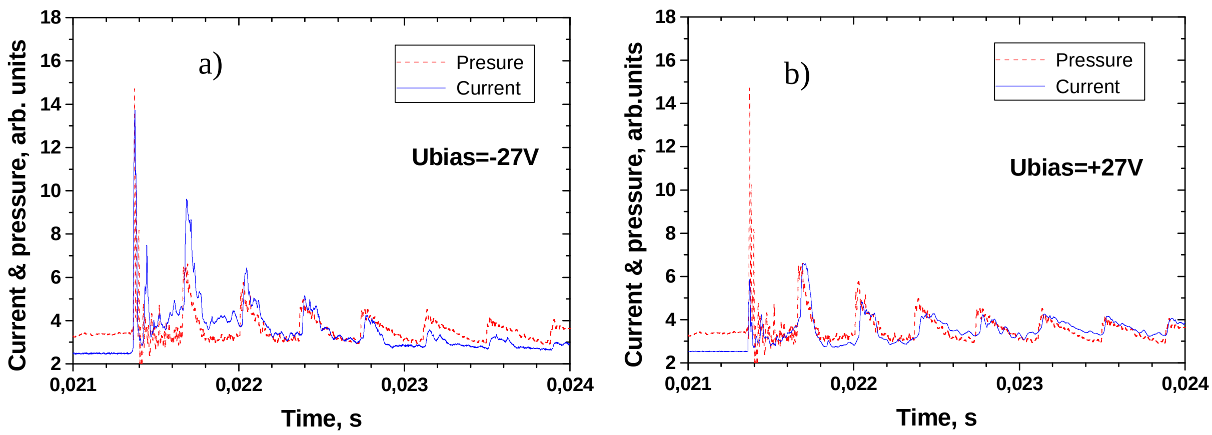

Figure 4. Comparison of pressure and probe current signals at different probe bias voltage: (a) – U_{bias} =-27V; (b) – U_{bias}=+27V. Pressure gauge and ionization probe are placed at chamber bottom in zone of autoignition (position #4). Initial pressure is 0.7MPa.

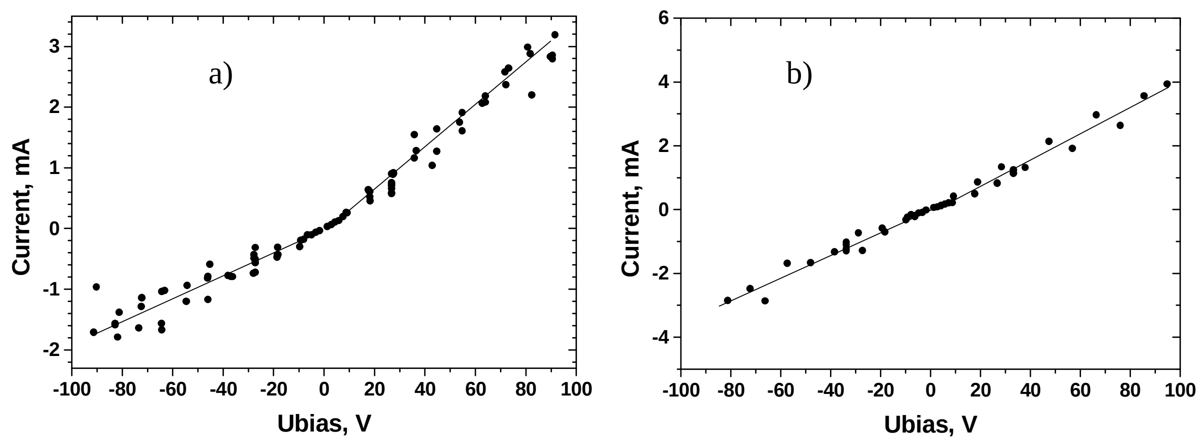

Figure 5. Current-voltage characteristics of electrical probe in burned gas (a) and in zone of autoignition (b). Solid line is the fitting of experimental data. Initial pressure is 0.7MPa.

To understand better the probe current formation it is useful to analyze probe current-voltage characteristics (CVC). In Fig.5 CVC obtained in area of autoignition and in burned gas are shown. In this and in following figures the current value corresponds to the amplitude of the first current peak detected by electrical probe. One sees that for burned gas CVC changes its slop with changing of U_{bias} polarity. CVC obtained in zone of autoignition is quasi-symmetrical, i.e. absolute value of current peak is only slightly depends on the polarity of voltage applied to the probe. It is worth noting that for burned gas CVC (Fig.5a) is similar to one in plasma containing positive and negative ions and also electrons. A positive branch of CVC obtained in burned gas is formed mainly by electron current which dominates over negative ion current due to higher electron mobility (compare amplitudes of positive and negative branches of CVC in Fig.5a). CVC presented in Fig.5b is typical for plasma consisting from positive and negative ions. Due to close mobility of positive and negative ions, the slop of positive and negative branches of CVC is about the same.

The difference in CVC in Fig.5a and Fig.5b would be explained by the processes of electron attachment and detachment in autoignition and burned gas zones. According to [12], the attachment and detachment of electrons on molecules O_2 would be considered as dominant. Following to [12] and taking into account the mixture composition used in our tests the characteristic times of electron attachment and detachment, τ_{att} and τ_{det}, respectively, would be obtained as:

$$\tau_{att} = 8.745 \cdot 10^{-17} \frac{T^3}{P^2} \cdot \exp\left(\frac{600}{T}\right), \tag{1}$$

$$\tau_{\det} = 4.4 \cdot 10^{-11} \cdot \frac{T^{1/2}}{P} \cdot \exp\left(\frac{5590}{T}\right). \tag{2}$$

In Eq.(1) and Eq.(2) the pressure P, and the characteristic times of attachment and detachment processes, τ_{att} and τ_{det}, are given in atmospheres and in seconds, respectively. The balance of electrons is given by the concurrence of attachment and detachment process.

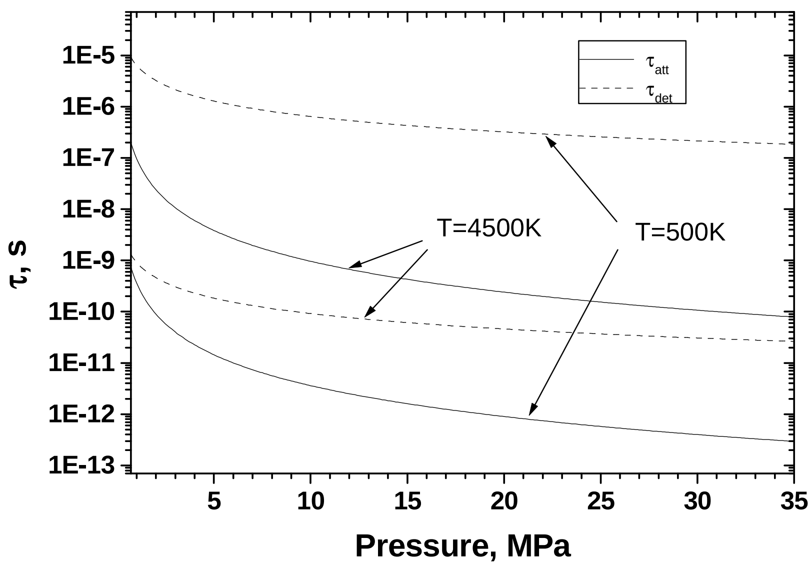

Figure 6. Characteristic times of electron attachment (solid line) and electron detachment (dashed line) versus pressure.

To estimate effect of high temperature on the electron attachment/detachment the calculation of electron life time were carried out for the characteristic gas temperatures in vicinity of the wall in autoignition and in burned gas regions. In Fig.6 calculated characteristic times of electron attachment and detachment are given versus pressure.

According to our model, in zone of autoignition chemical reaction zone interacts with electrical probe. This interaction is characterized by the presence of the layer of relatively cold unburned gas in vicinity of probe surface. In this layer which is similar to flame quenching layer [13], the combustion reactions are frozen. As in [14] we suggest that gas temperature in vicinity of wall is equal to the gas temperature before autoignition, i.e about 500K. Then, as it follows from results presented in Fig.6, in cold layer in vicinity of probe the process of electron attachment is dominant. For typical values of peak pressure 20-30MPa recorded in autoignition zone, the characteristic time of electron attachment is more than a few order of magnitude less than the characteristic time of electron detachment. It means that at these conditions in vicinity of probe there is no significant amount of free electrons and probe current in zone of autoignition is wholly due to drift of ions. This result explains the behaviour of CVC presented in Fig.5b.

For estimation of the time of electron attachment/detachment in burned gas zone we should suggest that gas temperature in vicinity of probe is equal to one behind the shock wave passing the cross-section of probe location. Evaluations based on the known intensity of shock wave give the value of about 4500K. Results presented in Fig.6 show that at this temperature the electron attachment occurs slower than electron detachment. Thus there is a probability for free electrons to be presented in burned gas. This conclusion is proved by the shape of CVC depicted in Fig.5a.

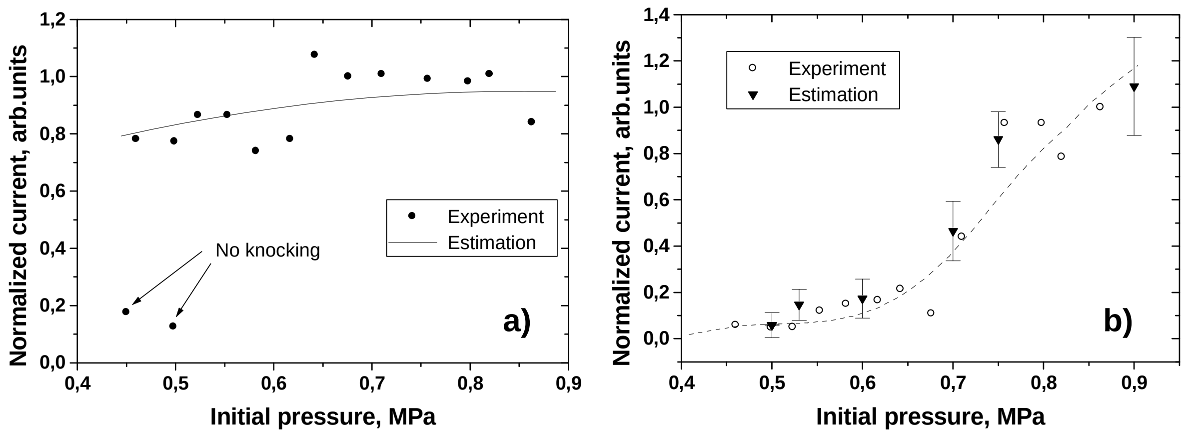

Figure 7. Normalized amplitude of peak current versus initial pressure in zone of autoignition (a) and in burned gas (b). In both cases bias voltage is -27V.

In Fig.7 pressure evolution of probe current is represented for different probe locations in combustion chamber. Pressure evolution of current were obtained for U_{bias}= -27V. Results presented in Fig.7a show that in zone of autoignition the peak current only slightly increases with the rise of an initial pressure. For comparison, the amplitude of probe current peak in combustion regime without knocking is also shown in this figure. Note that in knocking regime the probe current increases about 4 times relatively to one in non-knocking combustion, at the pressure and temperature increase of about 7-8 and 1.4-1.6 times, respectively.

In zone of autoignition the peak of ion current would be evaluated according to

$$I = n_i \cdot e \cdot \mu_i \cdot E \cdot S \, , \qquad (3)$$

where n_i, e, μ_i, E and S are the ion density, the elementary charge, the mobility of ions, the intensity of electrical field and probe surface, respectively. Let us analyse each parameter in Eq.(3).

At the thermal flame quenching, the probe current is formed by drift of charged species through the quenching layer of thickness δ_q under the difference of potential between flame and probe electrode, U_{bias} [8, 9]. In that case, the mean strength of electrical field E in this zone would be obtained as

$$E \approx U_{bias} / \delta_q \, . \qquad (4)$$

Quenching of transient laminar flame on a single wall is characterised by Peclet number, *Pe,* which is typically equalled to 3.5 for the case of head-on quenching [14 - 16]. So, the quenching distance would be evaluated taking into account the flame thickness, δ_l:

$$\delta_q = Pe \cdot \delta_l \approx 3.5 \cdot \frac{\lambda}{\rho \cdot S_u \cdot c_p} \quad . \qquad (5)$$

In Eq.(6) S_u is the laminar flame speed, λ is the thermal conductivity, ρ is the gas density and c_p is the thermal capacitance at constant pressure. Introducing the pressure dependence of laminar flame speed $S_u = S_o \cdot P^{-0.125}$ proposed in [17] Eq.(5) would be rewritten as

$$\delta_q = 3.5 \cdot \frac{R \cdot T}{M} \cdot \frac{\lambda}{S_o \cdot P^{0.875} \cdot c_p} \, , \qquad (6)$$

where S_o is the constant and R and M are the gas constant and the molecular weight, respectively. According to [18], ion mobility is a following function of pressure and temperature:

$$\mu_i = \frac{3}{8} \cdot \frac{e}{\sigma} \cdot \frac{1}{P} \cdot \left[\frac{1}{2} \cdot \pi \cdot k \cdot T \cdot \frac{m_i + m_N}{m_i \cdot m_N} \right]^{1/2} . \qquad (7)$$

Here σ is ion collision cross-section, k is the Boltzmann constant, m_i is the mass of ion and m_N is the mass of neutral species, P and T are the pressure and temperature, respectively.

Numerical modelling of flame ion composition showed that in stoichiometric heptane/air and methane/air flames the main positive ion is H_3O^+ and that concentration of this ion varies with pressure as $n_i \sim P^{-0.325}$ [10]. Thus, substituting the expressions for n_i, μ_i and $E=f(\delta_q)$ in Eq.(3) the pressure dependence of probe current in autoignition zone would be obtained in following form:

$$I = const \cdot \frac{c_p}{\lambda \cdot \sigma} \cdot P^{-0.55} \cdot \left[\frac{1}{T} \cdot \frac{m_i + m_N}{m_i \cdot m_N} \right]^{0.5} \qquad (8)$$

In Eq.(8) P is the peak pressure and T is the gas temperatures in quenching layer estimated as a mean value between the wall and the flame temperatures [14].

Equation (8) was used to predict the pressure evolution of peak probe current in zone of autoignition. Comparison of numerical and experimental results is presented in Fig.7a. One sees that analytical estimation based on Eq.(8) predicts rather well the peak current evolution versus an initial pressure. It proves our suggestion that in zone of autoignition the probe current is controlled by the processes in unburned gas layer, similar to ones at flame quenching phenomenon. It is worth noting, however, that prediction of exact value of peak probe current with Eq.(8) is rather difficult due to rather rough approach given by Eq.(4) as well as the lack of information on the flame ion composition at high pressures and temperatures.

In Fig.7b normalized values of peak current measured in burned gas zone, position #2 are depicted versus initial pressure. In this figure, dashed line is the fitting of experimental data. One sees that in burned gas area the pressure evolution of peak current is significantly different of one obtained in autoignition zone (for comparison see Fig.7a): one notes dramatically increasing of peak current at an initial pressure higher 0.7MPa. Comparing the amplitude of peak current in positions #1 and #2 for each test we found that peak current in position #1 is always smaller than one in position #2. It would be explained by attenuation of shock wave propagating along the combustion chamber and, consequently, by decreasing of thermal ionization of burned gas behind the shock.

Thermal ionization in neutral gas plasma is described by well known Saha equation:

$$\frac{n_i^{\,2}}{n_o} = 2 \cdot \left(\frac{2\pi \cdot m_e \cdot k \cdot T}{h^2} \right)^{3/2} \cdot \frac{g_e}{g_o} \cdot \exp\left(-\frac{E_i}{k \cdot T} \right). \qquad (9)$$

Here n_o is the gas density equalled $n_o=P/kT$, g_e and g_o are the statistical weights for electrons and neutrals, E_i, k and h are the ionization energy, the Boltzmann and Planck constants, respectively. By substitution in Eq.(3) the ion density from Eq.(9), the relative variation of probe current with initial pressure would be:

$$\frac{I^{(2)}}{I^{(1)}} = \left(\frac{P^{(1)}}{P^{(2)}} \right)^{1/2} \left(\frac{T^{(2)}}{T^{(1)}} \right)^{3/4} \cdot \exp\left[-0.5E \cdot \left(\frac{1}{T^{(2)}} - \frac{1}{T^{(1)}} \right) \right]. \qquad (10)$$

In Eq.(10) indexes (*1)* and (*2)* indicate different experimental conditions behind the shock waves. To compare with experiment our analytical prediction of pressure variation of ion current, gas temperature and pressure in Eq.(10) were initially evaluated taking into account experimental values of shock propagation velocity corresponding to different initial pressures. For evaluation of relative current variations the ionization energy E in Eq.(10) was taken as 15.7eV. This value corresponds to ionization energy of Ar which is the main component of burned mixture.

Comparison of experimental and numerical results for the probe peak current in burned gas area (probe position #2) is given in Fig.7b. In this figure the results of current evaluation from Eq.(10) are shown as solid up triangles. Numerical results are presented in normalized form. For the same initial conditions, due to shot-to-shot variation of shock velocity, each point of evaluated peak current in Fig.7b (solid down triangle) represents the average value of current calculated for 8-12 measurements of shock propagation velocity. Error bars show standard deviation of results. Shock wave velocity used for numerical evaluation of current was obtained from signal's delay at known distance between gauges #1 and #2. It is evident that pressure variations of peak current, numerical and experimental ones, correlate rather well in all range of initial pressures. It proves our suggestions on the thermal ionization nature of probe current in burned gas compressed and heated in transient shock. It is worth noting that in the frames of our simplified model the evaluation of absolute value of peak current in zone of burned gas would be difficult due to the interference of numerous shock waves in zone of probe electrodes having complex geometry. This interaction can't be predicted by 1D model of phenomenon used in our approach.

Conclusion

The possibility of knock detection with ionisation probe technique was tested. For interpretation of current signal the regime of knocking combustion was analysed using trace visualisation and pressure recording in different combustion chamber cross-sections. It was demonstrated that in zone of autoignition combustion regime is similar to adiabatic constant volume combustion (explosive combustion). Local and rapid energy extraction during autoignition of the end-gas generated shock and rarefaction waves propagating and interfering in zone of burned gas. Shock waves traversing the combustion chamber caused numerous oscillations of pressure and probe current signal. The frequency of these oscillations depends mainly on the size of combustion chamber.

Electrical probe signals recorded in autoignition zone and in burned gas at different values and polarities of bias voltage have analysed. Obtained probe current-voltage characteristics showed that in autoignition area the current to probe was formed by the drift of positive or negative ions, depending on bias voltage polarity. It was suggested that in zone of autoignition the probe current was formed by charged species produced in chemi-ionisation in the flame. In this case the probe current would be controlled by drift of ions from the flame front to the probe surface through the flame quenching layer. Based on this approach, in zone of autoignition the pressure evolution of peak probe current was predicted. It was found that pressure variations of peak current obtained numerically and experimentally correlate well.

Comparison the pressure evolutions of peak pressure and peak probe current recorded in zone of autoignition (position #4) also demonstrated good correlation between both signals. It allowed conclusion on the characterization of knock intensity from peak current when electrical probe is located in zone of autoignition.

In zone of burned gas the behaviour of probe current-voltage characteristics indicated the presence of electron component of probe current. It allows suggestion that in burned gas the main source of charged species is thermal ionisation behind the transient shock waves. Evaluation of probe current at these conditions allows prediction of relative variation of probe current versus initial pressure.

Comparing the results of pressure and current measurements in burned gas, any correlation was found between peaks of pressure and probe current. It is reasonable because, unlike the pressure signal, probe current depends on the intensity of ionization process in burned gas which is very sensitive to the gas temperature. Nevertheless, knocking can be detected by electrical probe located in burned gas. However, non-linear dependence of current signal on the knock intensity can create some difficulties in detection of early knocking.

Acknowledgments

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